REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
	Technical Papers	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT
Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048	11. SPONSOR/MONITOR'S NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20020917 038

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Leilani Richardson
a. REPORT	b. ABSTRACT	c. THIS PAGE	A		19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified			(661) 275-5015

4 items enclosed

⊛ Paper Rec'd After 30-day Deadline = 20 days until Deadline

FILE

MEMORANDUM FOR PRS (In-House/Contractor Publication)

FROM: PROI (STINFO)

05 August 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-AB-2002-202**
Bruce Chehroudi (ERC) & Doug Talley (PRSA), "High Pressure and Supercritical Combustion & Interactions of Jets with Acoustic Waves" (extended abstract only)

Talley 6174

AFOSR Contractors Meeting **(Statement A)**
(Colorado Springs, CO, 22 August 2002) (Deadline: 22 August 2002)

DISTRIBUTION STATEMENT A:
Approved for Public Release -
Distribution Unlimited

High Pressure and Supercritical Combustion: Interactions of Jets with Acoustic Waves

B. Chehroudi, ERC, Inc., and D.G. Talley, AFRL/PRSA
10 E. Saturn Blvd.
Edwards AFB, CA 93524-7660
bruce.chehroudi@edwards.af.mil douglas.talley@edwards.af.mil
(661)275-6175 (Chehroudi) or (661)275-6174 (Talley)

Task 93PL002

Abstract

The objective of this task is to determine the mechanisms which control the breakup, transport, mixing, and combustion of high pressure and supercritical droplets, jets, and sprays, both as these pertain to "steady" conditions as well as acoustically excited conditions. Previous results pertaining to "steady" conditions have now been augmented with the initiation of a study of the interaction of subcritical and supercritical jets with acoustic waves. Preliminary results suggest that supercritical jets do not couple with acoustic waves as strongly as near-critical and subcritical jets.

Introduction

Combustion chamber pressures in many existing and in most planned future liquid rocket engines exceed the critical pressure of the propellants, yet calculations in support of the design of such engines have in the past tended largely to assume conventional subcritical spray combustion processes. As the chamber pressure approaches and exceeds the critical pressure, however, many changes from conventional spray combustion can be expected. For example, the possibility of having distinct gas and liquid phases disappears at all temperatures when the pressure exceeds the critical pressure. Density varies smoothly, although possibly steeply, as a function of temperature with no discontinuous jumps. Surface tension and the enthalpy of vaporization vanish. Thus the substance is most appropriately referred to as neither a gas nor a liquid, but simply as a "fluid." Near the critical pressure, large variations in the density, thermal conductivity, and mass diffusivity can occur. For multi-component systems, the solubility of the lighter fluid in the heavier fluid increases as pressure approaches the critical pressure, the molecular diffusivity of the lighter fluid becomes more liquid-like, and mixture effects need to be taken into account in calculating the critical properties. Until recently, the mechanisms controlling injection and mixing under these conditions were not well understood, even to the extent that significant qualitative questions existed. However, considerable progress has been made over the past decade by research performed under this task [1-12] as well as by others [13-17].

Past results accomplished under this task include the successful production of transcritical cryogenic droplets [9], detailed shadowgraph measurements of the spreading rates of cryogenic jets over a range of subcritical to supercritical pressures [3,4,5,7], examination of the change in shear layer structure and the development of a semi-empirical model for predicting spreading rates over the full range of pressures [3,8], determination of the fractal dimension of the jets over the full range of pressures [1,8], and Raman scattering measurements of the structure of the initial region of subcritical and supercritical jets [6]. An important finding of these past studies was the finding that, at a high enough pressure exceeding the critical pressure, supercritical jets behave in many respects like low Mach number, variable density gas jets.

Here, attention is turned to the prospect of combustion instabilities and the potential for jets to interact with acoustic waves. Preliminary new results are presented which, apparently for the first time, reveal the effect of subcritical to supercritical pressures on the jet's ability to interact with externally driven transverse acoustic waves. Details not presented here may be found in refs. [2] and [12].

Experimental Approach

The experimental apparatus of previous studies [1-9] was modified to expose cryogenic jets to transverse acoustic waves traveling perpendicular to the axis of the jets. Cold nitrogen jets initially below the critical temperature of nitrogen (T_{cr} = 126.05 K) were injected into nitrogen at room temperature at various subcritical to supercritical pressures (P_{cr} = 3.42 MPa). The acoustic driver was a piezoelectric siren specially designed for high pressure applications by Hersh Acoustical Engineering, Inc. In order to maximize the acoustic power to which the jets were exposed, the acoustic waves were channeled into a high aspect

ratio rectangular channel into which the jets were injected vertically downward along the long axis of the cross section. The acoustic amplitudes reached between 161 to 171 dB at the dominant frequencies of 2700 and 4800 Hz. These frequencies are similar to those often observed in high frequency chamber-mode rocket combustion instabilities. The calculated wavelengths at these frequencies (13.1 and 7.4 cm) were both much longer than the jet exit diameter of .254 mm. Probably because the wavelengths were much longer than the jet diameter for both frequecies, the results for both frequencies were qualitatively similar. Consequently, only results at 2700 Hz are shown below. A picture of the experimental apparatus is given in Fig. 1, where the orientation of the acoustic waves relative to the jet is illustrated in the inset to the figure.

Results

It was found that a certain minimum oscillation amplitude was needed to bring about a detectable interaction with the jet. When a rapid transition is made from below to above this minimum value, a strong and transitory effect is observed, characterized by eruption of many drops and ligaments from the surface of the jet combined with amplification of the surface wave instabilities. When set at its highest achievable acoustic wave amplitude, the oscillation augmented the unstable surface waves and imposed a zigzag-shaped contour to the jet. In all cases it was found that the acoustic field tended to cause the jet to deform *in the mean* into an elliptical cross section with the major axis perpendicular to the direction of propagation of the acoustic waves. This deformation is the result of the Bernoulli effect. A circular shape exposed to a cross flow experiences higher velocities and hence lower pressures around the shoulders of the shape compared with the forward and aft stagnation regions. The result is forces that tend to distort the shape into an ellipse having a major axis perpendicular to the direction of the flow. In an acoustic field, although the velocity field is oscillating, the mean effect is still to produce lower pressures around the shoulders, producing mean forces that tend to distort the cross section into an ellipse.

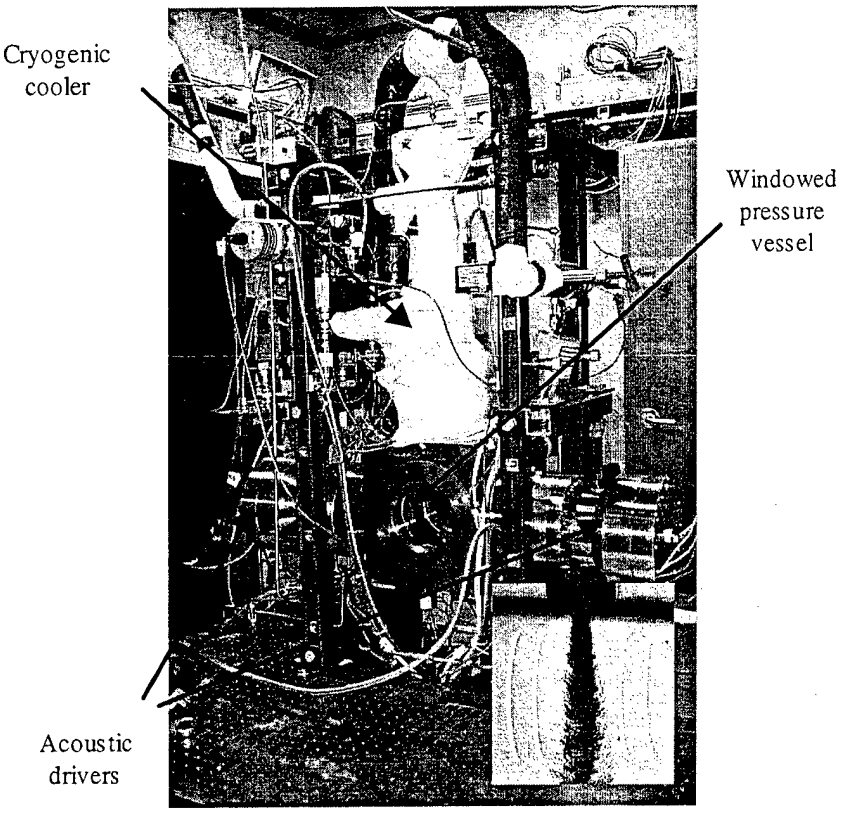


Figure 1.

Although the acoustic field always tended to distort the average cross section of the jet from a circle to an ellipse, the magnitude of the effect was found to depend on the case. Representative results showing the effect of the reduced pressure $P_r = P_{chamb} / P_{cr}$ are shown in Fig. 3. The top row of images in Fig. 3 corresponds to the acoustics being off, and the bottom row corresponds to the acoustics being on. The mass flow is the same in all cases, and the direction of wave propagation is perpendicular to the page. Quantitative measurements of such quantities as spreading angle, core length, and jet thicknesses with and without acoustics have been taken and are reported in refs. [2] and [12]. The overall trends observed are as follows. The effect of acoustic waves was largest near the critical pressure. The effect was smaller below the critical paper, where the jet is in a spray regime, but still reasonably large. Far enough above the critical pressure, however, when the jet is in a gas-like regime, there appears to be almost no effect of the acoustic waves. In all cases, the magnitude of the effect decreases as the velocity increases, which can be explained by fluid particles spending less time in the acoustic field as the velocity increases.

In an effort to better understand why the acoustic field had little observable effect on the supercritical jets, a literature survey was conducted. Several references having some features similar to the present study were found [17-21], but none were found to be fully relevant to the present conditions. Advantage was taken of previous findings under this task that at a high enough pressure above the critical pressure the jets behave in many respects like gas jets. Assuming this to be true, it was possible to plot the present conditions on a map developed by Rockwell [20] for planar gas jets. The result is shown in Fig. 2. Curves for both the 2700 Hz and the 4800 Hz cases are shown, where the arrow indicates the direction of increasing mass flow. It can be seen that the operating regimes of the present study were not the same as Rockwell's, so due note must be taken about the dangers of extrapolation. However, it appears possible to observe that the present results fall in a region which is not inconsistent with an expectation of small acoustic effects based on Rockwell's results. Further details concerning the above comparison are given in ref. [2].

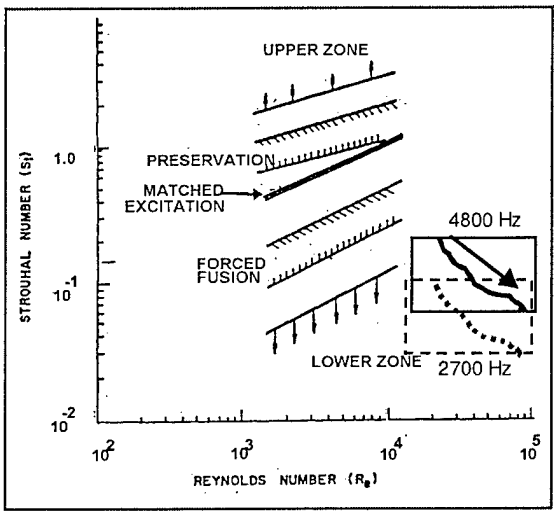


Figure 2

Relevance / Transitions

Previous observations that supercritical jets behave in many respects like gas jets at high enough pressures exceeding the critical pressure have one very important consequence: the likelihood that the vast body of existing literature regarding "conventional" gas jets can be used with some degree of confidence. Good indication now exists concerning when this will be the case and when it will not be. This is a significant improvement over the state of affairs that existed when this task was begun, when supercritical processes seemed fundamentally mysterious and there was no confidence about what to expect. Engine designers can now perform calculations with a greater degree of confidence.

The present acoustic results are preliminary and thus there has not been sufficient time for transition. However, they suggest one intriguing possibility. It seems possible that supercritical jets may have fewer ways to couple with acoustic waves than subcritical jets. Thus it seems possible that supercritical pressures might have enhanced combustion stability characteristics. Future planned research on acoustic effects will hopefully shed more light on this conjecture.

Summary and Conclusions

The effect of subcritical to supercritical pressures on the ability of a cryogenic nitrogen jet to couple with transverse acoustic waves has been studied, apparently for the first time, and preliminary results have been obtained. In all cases, the acoustic field tended to cause the jet to deform into an elliptical mean cross section, with major axis perpendicular to the direction of propagation, due to the Bernoulli effect. The magnitude of the deformation was greatest near the critical pressure, was smaller but still large at subcritical pressures, and was nearly unobservable at supercritical pressures. The latter result at supercritical pressures was consistent with the results of Rockwell [20]. The magnitude of the deformation also decreased in all cases as flow velocity increased, due to fluid particles having less time in the acoustic field. The results might imply that supercritical pressures have enhanced combustion stability characteristics.

References

1. Chehroudi, B., and Talley, D., "The Fractal Geometry of Round Turbulent Cryogenic Nitrogen Jets at Subcritical and Supercritical Pressures," submitted to *Atomization and Sprays*.
2. Chehroudi, B., and Talley, D.G., "Interaction of Acoustic Waves with a Cryogenic Nitrogen Jet at Sub- and Supercritical Pressures," 40th AIAA Aerospace Sciences Meeting and Exhibit, paper AIAA 2002-0342, Reno, NV, 14-17 January, 2002.

3. Chehroudi, B., Cohn, R., and Talley, D., "Cryogenic Shear Layers: Experiments and Phenomenological Modeling of the Initial Growth Rate Under Subcritical and Supercritical Conditions," *International Journal of Heat and Fluid Flow*, 2002. (To appear)
4. Chehroudi, B., Talley, D., and Coy, E., "Visual Characteristics and Initial Growth Rates of Round cryogenic Jets at Subcritical and Supercritical Pressures," *Physics of Fluids,* Vol. 14, No. 2, February 2002.
5. Chehroudi, B., Cohn, R., and Talley, D.G., "The Behavior of Cryogenic Shear Layers under Supercritical Conditions," 2nd International Symposium on Turbulence and Shear Flow Phenomena, Stockholm, Sweden, 27-29 June 2001.
6. Chehroudi, B., Cohn, R., Talley, D., and Badakhshan, A., "Raman Scattering Measurements in the Initial Region of Sub- and Supercritical Jets," AIAA/SAE/ASME/ASEE Joint Propulsion Meeting, AIAA paper 2000-3392, Huntsville, AL, 17-19 July 2000.
7. Chehroudi, B., Talley, D.G., and Coy, E.B., "Initial Growth Rate and Visual Characteristics of a Round Jet into a Sub- to Supercritical Environment of Relevance to Rocket, Gas Turbine, and Diesel Engines," AIAA paper 99-0206, Reno, Nevada, 1999.
8. Chehroudi, B., Talley, D., and Coy, E. "Fractal geometry and growth rate of cryogenic jets near critical point," AIAA Paper 99-2489, 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Los Angeles, CA, June 20-24, 1999.
9. Mayer, W.O.H., Schik, A.H.A., Vielle, B., Chauveau, C., Gokalp, I., Talley, D.G., and Woodward, R.D., "Atomization and Breakup of Cryogenic Propellants Under High Pressure Subcritical and Supercritical Conditions," *Journal of Propulsion and Power*, vol. 14, no. 5, September-October 1998.
10. Woodward, R. D. and Talley, D. G. "Raman imaging of transcritical cryogenic propellants," AIAA Paper 96-0468, Reno, Nevada, January 1996.
11. Anderson, T.J., Woodward, R.D., and Winter, M. "Oxygen Concentration Measurements in a High Pressure Environment Using Raman Imaging," AIAA Paper 95-0140, 33rd Aerospace Sciences Meeting and Exhibit, January 9-12, Reno, NV, 1995.
12. Chehroudi, B., and Talley, D., "Preliminary Visualizations of Acoustic Waves Interacting With Subcritical and Supercritical Cryogenic Jets," 15th Annual Conference on Liquid Atomization and Spray Systems, Madison, WI, 14-17 May 2002.
13. Smith, J. Klimenko, D. Clauß, W., and Mayer, W., "Supercritical LOX/Hydrogen Rocket Combustion Investigations Using Optical Diagnostics," 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, paper AIAA-2002-4033, Indianapolis, IN, 7-10 July 2002.
14. Mayer, W., and Tamura, H., "Propellant Injection in a Liquid Oxygen/Gaseous Hydrogen Rocket Engine," *Journal of Propulsion and Power*, vol. 12, no. 6, pp 1137-1147, 1996.
15. Oefelein, J. C. and Yang V. "Modeling High-pressure Mixing and combustion Processes in Liquid Rocket Engines," *Journal of Propulsion and Power*, vol. 14, no. 5, September-October, 1998.
16. Bellan, J., "Supercritical (and Subcritical) Fluid Behavior and Modeling: Drops, Streams, Shear and Mixing Layers, Jets and Sprays", *Progress in Energy and Combustion Science*, special anniversary edition, vol. 26, pp. 329-366, 2000.
17. Miesse, C. C., "The Effect of Ambient Pressure Oscillations on the Disintegration and Dispersion of a Liquid Jet," *Jet Propulsion*, 25, pp. 525-530, 534, 1955.
18. Buffum, F. G., and Williams, F. A., "Response of Turbulent Liquid Jets to Transverse Acoustic Fields," Proceedings of the 1967 Heat Transfer and Fluid Mechanics Institute, Edited by P. A. Libby, D. B. Olfe, and C. W. Van Atta, 1967, pp. 247-276, 1967.
19. Heidmann, M. F. and Groeneweg, J. F., "Analysis of the Dynamic Response of Liquid Jet Atomization to Acoustic Oscillations," NASA Technical Note, NASA TN D-5339, July, 1969.
20. Rockwell, D. O., "External Excitation of Planar Jets," *Journal of Applied Mechanics*, pp. 883-891, December 1972.
21. Becker, H. A. and Massaro, T. A., "Vortex Evolution in a Round Jet," *Journal of Fluid Mechanics*, Vol. 31, Part 3, pp.435-448, 1968.

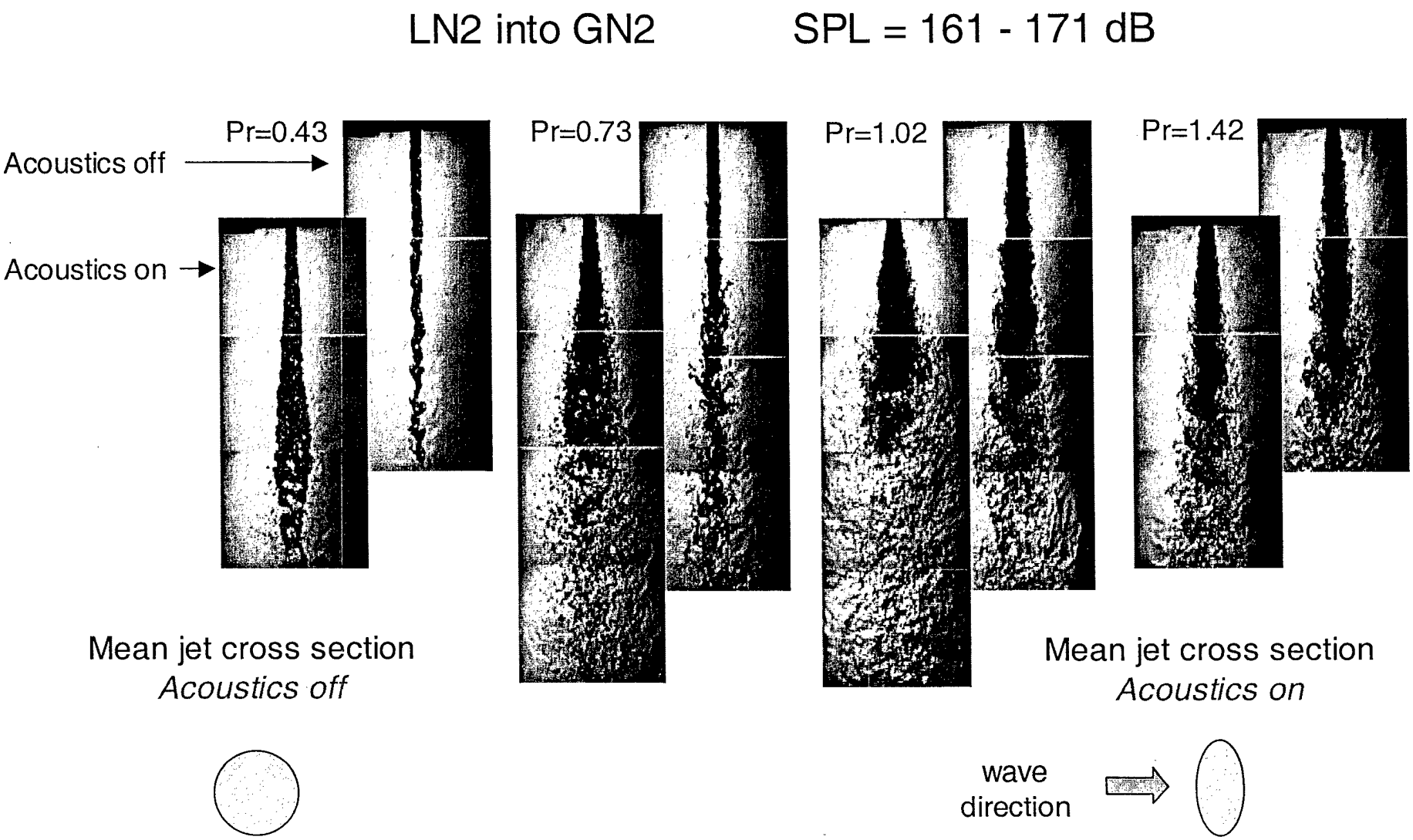
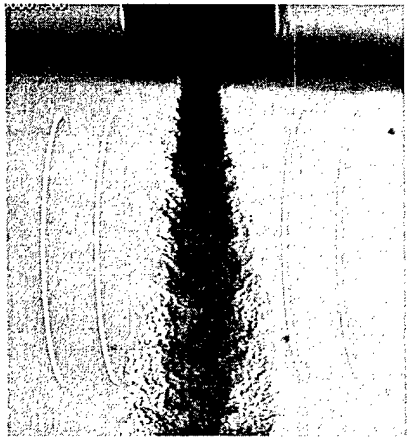
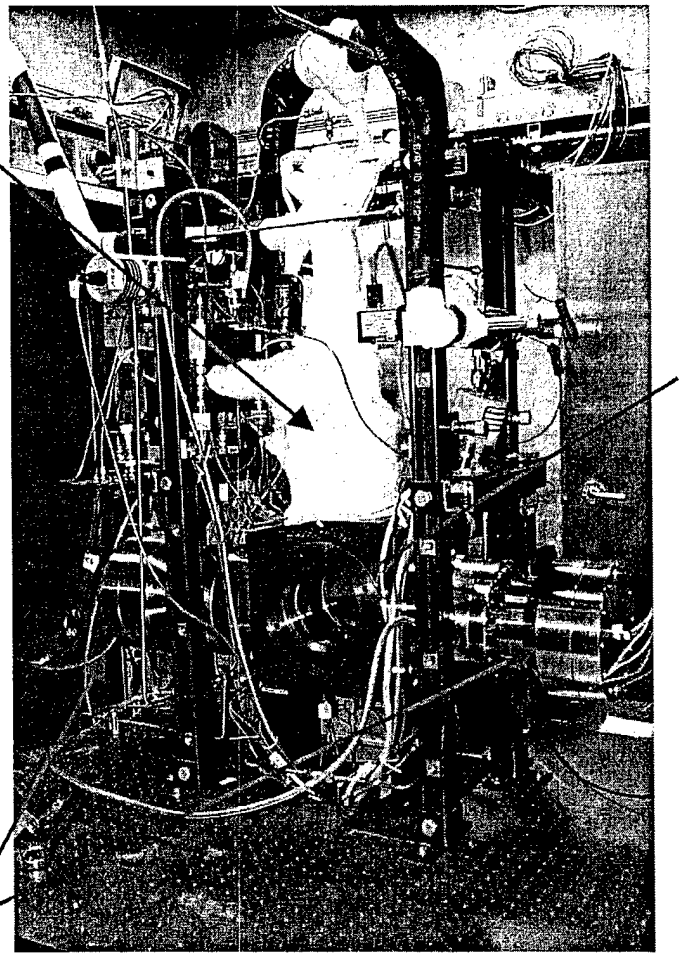

LN2 into GN2
SPL = 161 - 171 dB
Pr=0.43
Pr=0.73
Pr=1.02
Pr=1.42
Acoustics off
Acoustics on
Mean jet cross section
Acoustics off
Mean jet cross section
Acoustics on
wave
direction

Figure 3.

Forcing subcritical and supercritical jets with acoustic waves



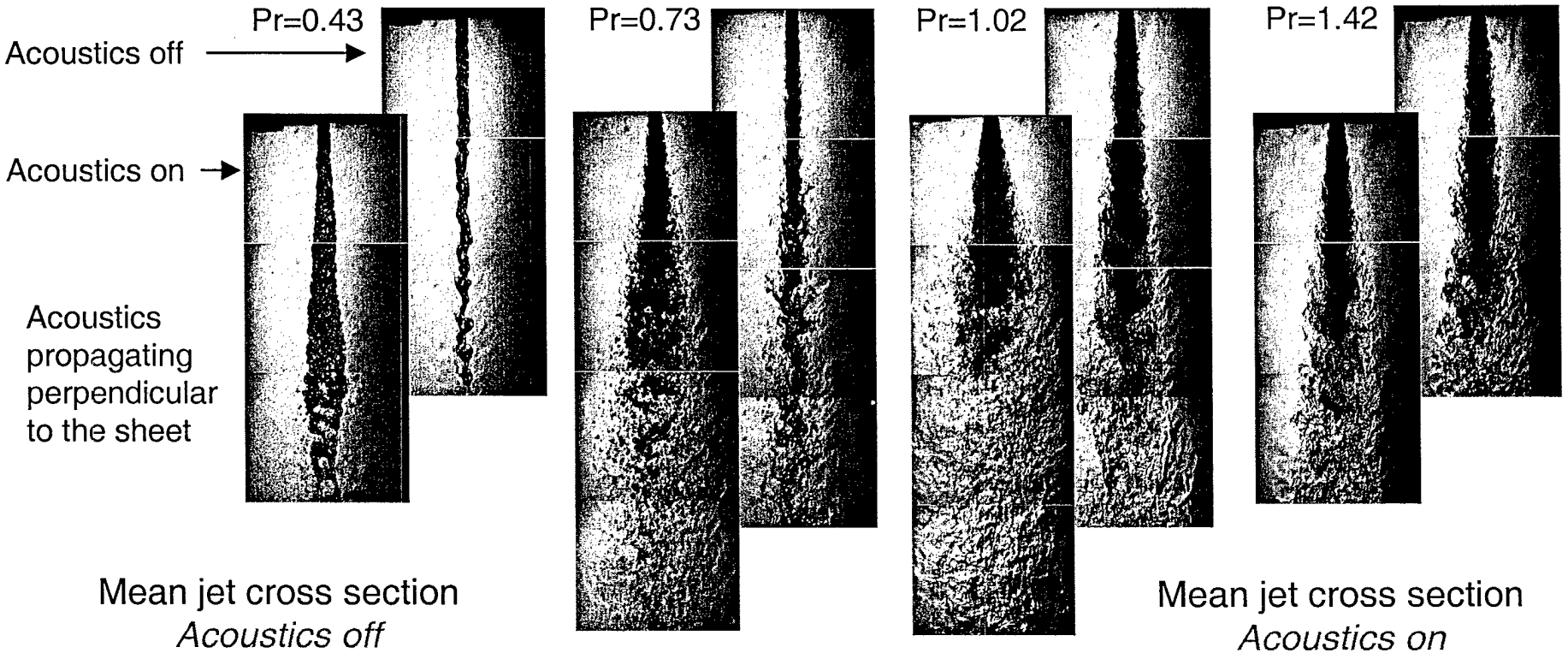
Acoustic waves impinging on jet



Chehroudi and Talley

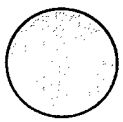
Acoustic results

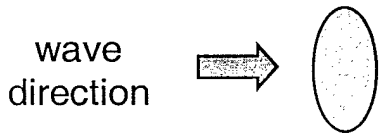
LN2 into GN2 SPL = 161 - 171 dB



Mean jet cross section
Acoustics off

Mean jet cross section
Acoustics on

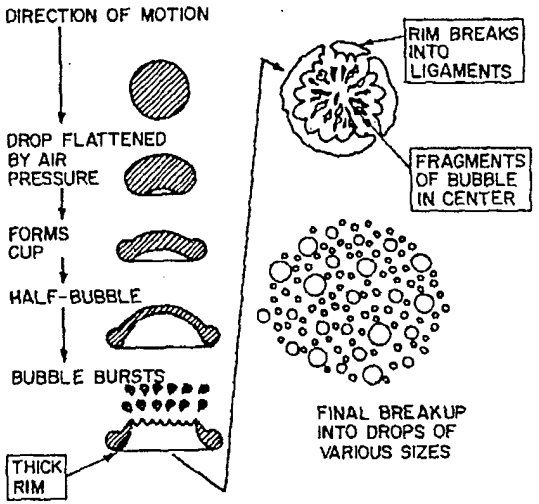


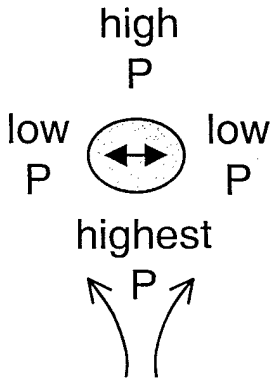


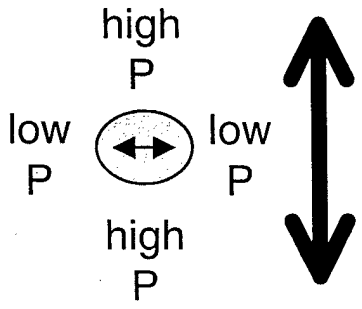
Chehroudi and Talley, AIAA paper 2002-0342

Jet deformation mechanism

Bag breakup of drops







- Drops flatten perpendicular to the flow before breaking up because the higher velocities around the shoulders cause lower pressures there due to the Bernoulli effect.
- Similar pressure imbalances are set up, *in the mean*, around a jet (or drop) in an acoustic field.
- Therefore the jet deforms in the mean.

Falling drop

Jet in acoustic field

Chehroudi and Talley

Main conclusions from acoustics observations

- The effect of acoustics:
  - is largest near the critical pressure.
  - is strong at subcritical pressures.
  - decreases to negligible at supercritical pressures
- The effect of acoustics decreases at all pressures as jet velocity increases (residence time in the acoustic field decreases)

Potential future success story

- Supercritical pressures may have enhanced combustion stability characteristics.